



## Relating Cost of Energy to the Electromagnetic Design of Wind Turbine Generators

Henriksen, Matthew Lee; Jensen, Bogi Bech

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# Relating Cost of Energy to the Electromagnetic Design of Wind Turbine Generators

Matthew L. Henriksen

Technical University of Denmark

[mlee@elektro.dtu.dk](mailto:mlee@elektro.dtu.dk)

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# Outline

- 1 Introduction
- 2 Cost of Energy - Background
- 3 Wind Turbine Components
- 4 Comparing Generator Designs by Cost of Energy
- 5 Conclusion

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# Introduction

## Wind Turbine Generators with Reduced Reliance on Rare Earth Metals

Three year PhD project in electrical machine design. Targets include:

- Design of PMSM wind turbine generators
- Development of optimal machine design process
- Comparison of alternative machines with PMSM

# Introduction

## Project Status

- Half-way point has been passed.
- Focus is shifted to non-RE machines
- Delivery in Sept. 2014

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# Cost of Energy

A key metric which is often cited in comparing energy sources is the cost of energy (COE).



# Estimating the Cost of Energy

- When considering projects, those which would give the lowest COE stand to be the most profitable.
- What must be known to estimate the COE?
  - Capital expenditure (CAPEX) - purchasing and installing
  - Operational expenditure (OPEX) - maintaining and operating
  - Annual energy production (AEP) - the total amount of energy produced in a year

$$COE = \frac{CAPEX + OPEX}{AEP} \quad (1)$$

# Wind Turbine Cost of Energy

For wind turbines, estimating the CAPEX and OPEX is very complicated. A large number of factors must be incorporated:

## CAPEX

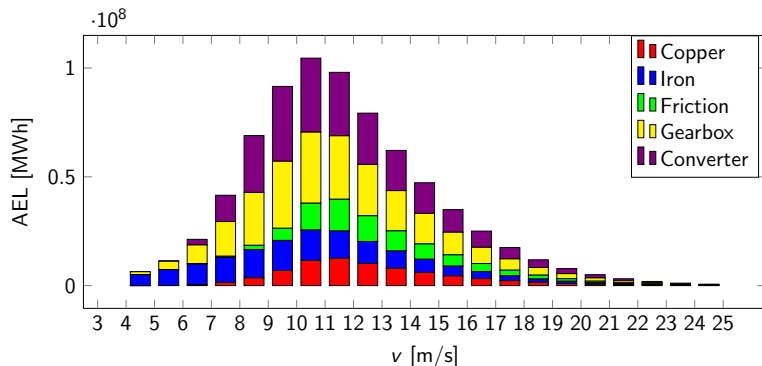
- Equipment
- Transportation
- Construction

## OPEX

- Operation
- Maintenance
- Condition monitoring

# Annual Energy Production

Need a process for estimating the yearly losses



For a wind climate described by Weibull parameters  $k=2$  and  $A = 9$

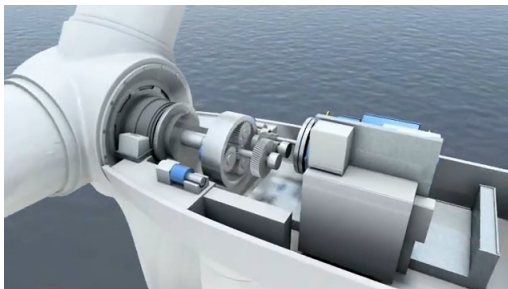
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# Power Conversion

Wind turbine topologies are characterized by the selection and usage of the power conversion devices:

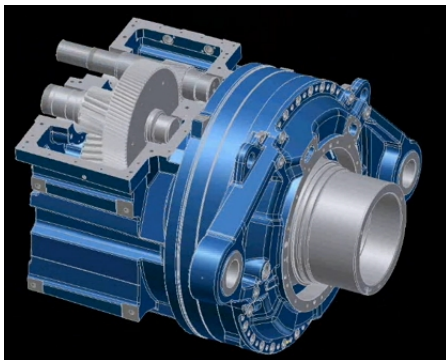
- Gearbox
- Power electronic converter
- Generator



<sup>1</sup>Image from [www.ZF.com](http://www.ZF.com)

# Gearboxes

Gearboxes (when present) reduce the input torque to the generator and increase the speed.



2

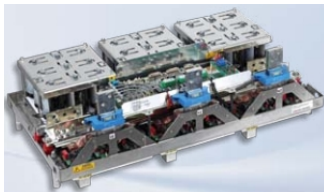
<sup>2</sup>Image from [www.ZF.com](http://www.ZF.com)

# Gearboxes - modeling

- May consider single-stage, or multi-stage configurations
- Rated losses:  $0.5\% P_{rated}$  for planetary stages,  $1\% P_{rated}$  for parallel stages
- Split into torque dependent and torque independent components
- Assumed cost:  $3.5\text{€}/\text{kW}$

# Power electronic converter

- Power electronic converters convert variable electrical quantities of the generator to grid compliant frequency and amplitude.



3



4

- Nowadays, the discussion is centered on two major types:
  - Fully rated, used with synchronous generators
  - Partially rated, used with doubly-fed induction generators

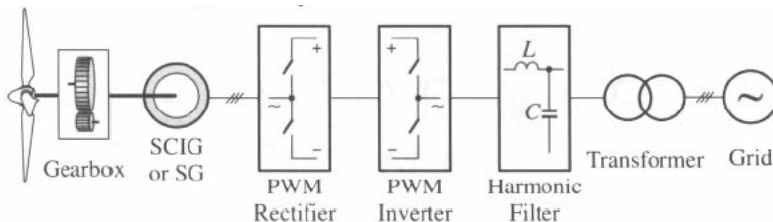
<sup>3</sup>Image from [www.infineon.com](http://www.infineon.com)

<sup>4</sup>Image from [www.ABB.com](http://www.ABB.com)



# Power converter - modeling

- 6-pulse, fully rated, back to back with DC link
- Rated losses:  $2\% P_{rated}$
- Losses split into constant, linear current- and quadratic current-dependent components
- Assumed cost: 30€/kVA



# Generators

Generators convert mechanical power to electrical power.



5



6

<sup>5</sup>Image from [www.theswitch.com](http://www.theswitch.com)

<sup>6</sup>Image from [www.ingeteam.com](http://www.ingeteam.com)

# Generator - modeling

- PMSM with NdFeB, SCIG, SynRel, others...
- Rated losses: found by FEA
- Assumed cost: by material
  - Copper: 15€/kg
  - Laminations: 5€/kg
  - Magnet: 75€/kg

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# Generator Design

Torque production is a matter of size, current, and flux density.

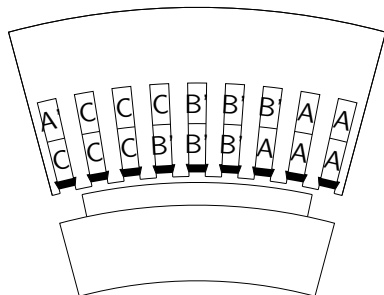
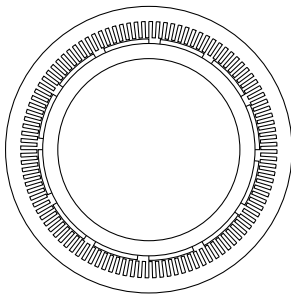
$$T_{max} = \sqrt{2} V A \hat{B} \quad (2)$$

The designer must choose the proportions of these three to be taken, in order to achieve the required torque.

# Generator Design

Moving on, many degrees of freedom may be present:

- Axial length
- Inner radius
- Outer radius
- Air gap length
- Materials
- Air gap length
- Slot dimensions
- And many more...



# Generator Design

Several aspects of the generator will influence the cost of energy:

- Cost
- Losses
- Reliability

My philosophy: optimize the machine design to reduce the cost of energy

# Design Study

The expected cost of energy is assessed for PM machines designed by three optimization strategies:

- 1 Full load efficiency
- 2 Cost of generator
- 3 Cost of energy

The design is based on a fictional 3MW wind turbine, with the generator driven at 1200rpm through a 3-stage gearbox.

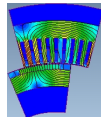
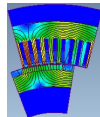
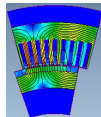
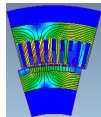
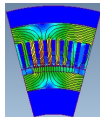


# Optimal Design

A parameterized generator model is analyzed, with several constraints:

- Rated torque requirement
- Slot dimensions (not too thin)
- Synchronous reactance ( $\geq 0.5\text{pu}$ )
- Air gap length (no smaller than 0.1% of diameter)

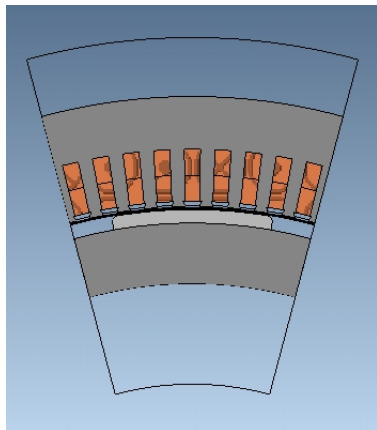
Design variables include electrical loading, magnet height, and most mechanical dimensions.



# Results

## Optimized for generator cost

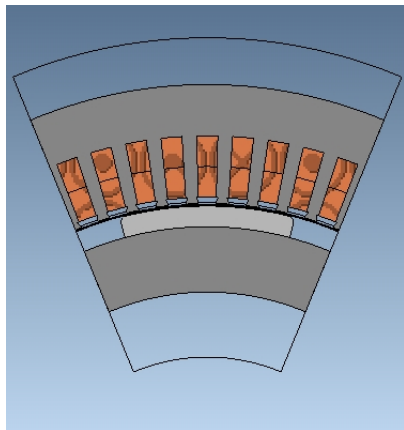
- Length: 0.5m
- Diameter: 1.0m
- Cost: 34.2k€
- Full load efficiency: 96.4%
- Estimated cost of energy:  
0.28€/kWh



# Results

## Optimized for full load efficiency

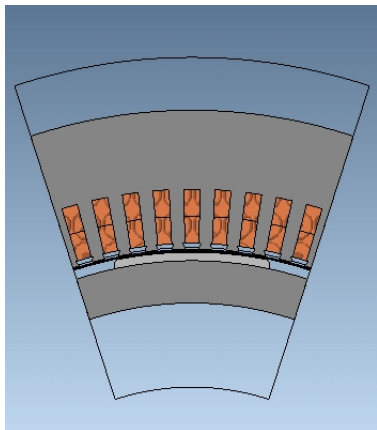
- Length: 1.0m
- Diameter: 0.64m
- Cost: 49.5k€
- Full load efficiency: 98.4%
- Estimated cost of energy: 0.26€/kWh



# Results

## Optimized for cost of energy

- Length: 0.8m
- Diameter: 0.78m
- Cost: 38.7k€
- Full load efficiency: 97.9%
- Estimated cost of energy:  
0.25€/kWh



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# Conclusion

The electromagnetic design of the generator is related to the cost of energy through several aspects:

- Losses
- Material cost
- Operational cost

Taking losses and material cost into consideration, optimal generator design for cost of energy has been demonstrated for PMSM wind turbine generators. The approach tends to yield a result between optimizing for efficiency and optimizing for cost reduction.

# Conclusion

## Acknowledgements

Thanks to DONG Energy for sponsoring the PhD project Wind Turbine Generators with Reduced Reliance on Rare Earth Metals.

Thank you!

Questions?